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A system in balance? – Implications of deep vertical mixing for the nitrogen budget in the northern Red Sea, including the Gulf of Aqaba (Eilat)

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Abstract

We investigated the implications of deep winter mixing for the nitrogen budget in two adjacent systems, the northern Red Sea proper, and the Gulf of Aqaba. Both are subtropical oligotrophic water bodies. The main difference is that in the gulf deep winter mixing takes place regularly, whereas the northern Red Sea proper is permanently stratified. In the Gulf of Aqaba, we observed significantly lower nitrate deficits, i.e. deviations from the Redfield ratio, than in the northern Red Sea proper. Assuming that other external inputs and losses in N or P are very similar in both systems, the higher nitrate deficit can be explained by either lower nitrogen fixation in the (stratified) northern Red Sea, which seems unlikely. An alternative explanation would be higher rates of benthic denitrification than in the gulf. By comparing the two systems we have indirect evidence that benthic denitrification was much lower in the Gulf of Aqaba due to higher oxygen concentrations. This we attributed to the occurrence of deep winter mixing, and as a consequence, the nitrate deficit was close to zero (i.e. N:P ratio close to "Redfield"). If both nitrogen fixation and benthic denitrification take place, as in the northern Red Sea proper, the result was a positive nitrate deficit (i.e. a deficit in nitrate) in the ambient water. The nitrate deficit in the northern Red Sea was observed in spite of high iron deposition from the surrounding desert. Our results strongly support the concept of nitrogen as the proximate, and phosphate as the ultimate limiting nutrient for primary production in the sea. This must not be neglected in efforts for protecting the adjacent reefs against eutrophication.

1 Introduction

Nitrogen (N) and phosphorus (P) are the nutrients potentially limiting phytoplankton production in the oceans. From considerations of the N:P ratios in phytoplankton cells, and in the ambient water, and from nutrient enrichment experiments, nitrogen was proposed to be the limiting nutrient (e.g. Codispoti, 1989; referred to as the "biologist's

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view”). Considering the evolution of biogeochemical cycles in the context of the evolution of the involved enzyme systems, Falkowski suggested that nitrogen is the limiting nutrient for primary production on geological time scales (Falkowski, 1997; Codispoti, 1997). On the other side, it is argued that nitrogen cannot be the limiting nutrient of primary production as long as nitrogen fixation can take place. Since there is no equivalent influx process to the system for phosphorus, the N:P ratio could principally be adjusted to phytoplankton demands by nitrogen fixation. Thus, on the long term phosphorus must be the nutrient controlling phytoplankton productivity (e.g. Tyrrell, 1999; Toggweiler, 1999; referred to as the “geochemist’s view”). By model calculations, Tyrrell (1999) pointed out that the proximate and the ultimate limiting nutrient (PLN and ULN) do not have to be the same nutrient species, even in a steady state system. The PLN “represents the local limiting nutrient according to Liebig’s law”, whereas the ULN “represents the nutrient whose supply rate forces total system productivity over long timescales” (Tyrrell, 1999). The model runs demonstrated that in marine systems nitrate is the PLN in surface waters, whereas phosphate is the ULN for the system.

The question whether nitrogen or phosphorus is regulating primary production in the ocean is connected to the question after the cause for the nitrate deficit that is observed in vast parts of the oceans (e.g. Gruber and Sarmiento, 1997). The mechanisms responsible for the nitrate deficit are not yet fully resolved. The imbalance between denitrification and nitrogen fixation is considered to play the key role in that. It is still under debate, whether the nitrate deficit is partly caused by iron limitation of nitrogen fixers (e.g. Falkowski, 1997; Toggweiler, 1999; Wu et al., 2000; Sañudo-Wilhelmy et al., 2001; Tyrrell et al., 2003). An alternative explanation was proposed by the competition between nitrogen-fixing and other phytoplankton (Tyrrell, 1999).

The present study investigates the oligotrophic northern part of the Red Sea, including the Gulf of Aqaba. The Gulf of Aqaba and the northern Red Sea proper (in the following referred to as the northern Red Sea) are adjacent water bodies that are connected by a shallow sill. Whereas the Red Sea can be considered as permanently stratified (Plähn et al., 2002), deep winter mixing occurs regularly in the gulf (Wolf-

Vecht et al., 1992; Genin et al., 1995; Manasrah et al., 2004). The aim of the present study is to investigate the implications of the deep mixing for the nitrogen budget, in particular for the nitrate deficit in the water column, by a comparative analysis of the two systems. Al-Qutob et al. (unpubl. manuscript) found N:P ratios close to the Redfield ratio in the Gulf of Aqaba. By applying the concept of the nitrate deficit (e.g. Gruber and Sarmiento, 1997; Tyrrell and Lucas, 2002) we address the question, whether the nitrogen input and loss processes are in balance in the Gulf of Aqaba. We report on field observations from a unique marine system that provide evidence for reconciling "the biologist's and the geochemist's views".

2 Study site

The Red Sea has a tectonic origin as a transform fault of the East African Rift Valley system. It is located in an arid climate zone with negligible precipitation and terrestrial run-off. High evaporation rates in the region (1 cm d^{-1} in the gulf, cf. Wolf-Vecht et al., 1992; and 2.1 m a^{-1} in the Red Sea, Sofianos et al., 2002) cause a negative hydrological budget which is compensated by a net water inflow into the Red Sea through the shallow sill (140 m) at Bab-al-Mandeb (Longhurst, 1998). The thermohaline circulation pattern at Bab-al-Mandeb of surface inflow and subsurface outflow (Longhurst, 1998) is repeated at the second shallow sill (250 m) at the Straits of Tiran (Reiss and Hottinger, 1984). During the study period, inflow into the gulf occurred in the 35–70 m layer, and outflow below 70 m (Manasrah et al., 2004). Water renewal times in the top 200 m layer in the Red Sea were estimated to six years, and for the entire water body to around 200 years (UNEP, 1997), whereas a recent study report on 30–45 years for the deep water in the Red Sea (Plähn et al., 2002). The water renewal time in the Gulf of Aqaba was determined to between 1 and 2 years (cf. Hulings, 1989). The waters are highly transparent with euphotic depths (1-% light level) in the range of 77–105 m in the Gulf of Aqaba, and 74–94 m in the northern Red Sea during the study period (Stambler, 2005). The entire area is surrounded by desert from which large amounts of dust are deposited on the water surface. Even though both water bodies are closely interconnected, they differ in their hydrodynamic regimes. The Red Sea is permanently stratified with high nutrient concentrations in deep waters being effectively separated from the nutrient-depleted euphotic zone by a strong pycnocline (e.g. Longhurst, 1998). By contrast, in the Gulf of Aqaba deep winter mixing occurs regularly (Wolf-Vecht et al., 1992; Genin et al., 1995; Manasrah et al., 2004), in some years even down to the sea floor at the northern end of the gulf (i.e. >700 m). The southern Red Sea is considered a highly productive system (Reiss and Hottinger, 1984; Longhurst, 1998). As the surface waters flow north, the dissolved nutrients are removed by phytoplankton uptake, so that 2000 km to the north nutrient-depleted surface waters enter the Gulf of Aqaba through the Straits of Tiran (Reiss and Hottinger, 1984). In the gulf, the vertical distribution of nutrients is the result of alternating stratification during summer, then resembling the situation in the Red Sea, and deep vertical mixing in winter, resulting in a homogeneous distribution of nutrients within the mixed layer (e.g. Al-Qutob et al., unpubl. manuscript). Like in most (sub)tropical oligotrophic seas, nitrate was mostly considered to be the controlling nutrient for primary production in the Red Sea, including the Gulf of Aqaba (Levanon-Spanier et al., 1979; Reiss and Hottinger, 1984; Weikert, 1987; Badran et al., 2005). By contrast, Naqvi et al. (1986) reported on nitrogen export from the Red Sea into the Gulf of Aden, and Hulings considered phosphate as the limiting nutrient for primary production in the Gulf of Aqaba (cf. Hulings, 1989). However, a recent study reports on co-limitation of both nutrients (Al-Qutob et al., unpubl. manuscript). In both water bodies extensive blooms of *Trichodesmium* do occur (Kimor and Golandski, 1977; Weikert, 1987; Böttger-Schnack and Schnack, 1989; Longhurst, 1998; Post et al., 2002).

3 Methods

3.1 Field measurements

The nutrient regime in the Gulf of Aqaba was monitored for three years from January 1997 to December 1999 by monthly one-day cruises to the routine station of the Red Sea Program at the northern tip of the gulf (Station I, Fig. 1). Additional data were collected in the Gulf of Aqaba, and in the northern Red Sea during the 44/2 cruise of RV "Meteor" from February 21 until 8 March 1999.

For some unknown reason, the N:P ratios observed in the gulf during the two-weeks RV "Meteor" 44/2 cruise in February/March 1999 were in general lower than the values derived from the one-day cruises to Station I. This applied even to the one-day cruises in Spring 1999 just before and after the "Meteor" cruise. The data were thoroughly checked and found to be consistent. It seemed to be a systematic trend in the entire data set from the "Meteor" cruise. Therefore, and because no data from other cruises were available for the northern Red Sea, we considered in the present study only the data collected during the "Meteor" cruise for the comparison of the two systems.

Sample collection was performed by a trace metal-clean rosette with 10-L Niskin bottles using clean Tygon tubing. Sample tubes were thoroughly flushed with sample water before filling. Measurements of nutrient concentrations were carried out within 24 h after sampling, meanwhile samples were stored cool and dark. Nutrient concentrations were measured by a Flow Injection Analyzer (FIA Quick – Chem 8000). Oxygen concentrations were determined by Winkler titration. Mixing depths were determined from CTD-data and nutrient (mainly nitrate) gradients. Trace metal concentrations were determined by atomic absorption spectrometry (data not shown).

3.2 Calculation of the nitrate deficit and the apparent oxygen utilization (AOU)

The apparent oxygen utilization (AOU) in the water column was calculated for each vertical profile by integrating the saturated oxygen concentration according to the actual

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vertical distribution of temperature and salinity. Then the depth-integral of the actual measurements was subtracted.

The water-column nitrate deficit was calculated by subtracting the depth-integral of total oxidized nitrogen concentrations from the 16-fold of the vertical integral of phosphate concentrations.

4 Results

4.1 Mixing depths

The "Meteor" cruise took place during the height of the mixing season in 1999. At the beginning of the cruise, mixing depths in the Gulf of Aqaba were about 200–300 m with a slight peak in the middle stations (II–IV), and lower values at both ends of the gulf (stations I, V, and VI). During the two-weeks period of the cruise, the mixing depth in the gulf increased, reaching maximum values at the northern end of the gulf (station I). By the end of the cruise, a north-south gradient had established with values between 250 m in the south, and 400–500 m in the north. By contrast, in the northern Red Sea no such pattern nor any trends were observed. While surface cooling and wind stirring allowed mixing down to 500 m in the Gulf of Aqaba, mixing depths in the northern Red Sea were generally in the range of 20–75 m, interrupted by single, local mixing events reaching about 100 m depth. The mixing hardly exceeded the euphotic zone (74–94 m; Stambler, 2005). Thus, in the northern Red Sea there was virtually no exchange in oxygen or nutrients between the upper mixed layer and the deep waters, not even during the mixing season.

4.2 Nitrate deficit and N:P ratio

The average N:P ratio for each system was determined by a linear regression analysis of the total oxidized nitrogen concentrations versus phosphate concentrations. In addition, the average nitrate deficit was calculated for each pair of total oxidized nitrogen and phosphate measurements. We followed the definition by Tyrrel and Lucas (2002): $\Delta N=16\times[PO_4^{3-}]-[NO_3^-]$, except that we used total oxidized nitrogen instead of nitrate, because the presence of nitrite in the water column was attributed to nitrite excretion by phytoplankton (Al-Qutob et al., 2002), presumably originating from previous phytoplankton uptake of nitrate.

The differences between the two systems were highly significant: The differences in N:P ratios were tested by a General Linear Model ($p<0.005$), nitrate deficits were compared by a two-sided t-Test ($p=9.9\times10^{-10}$). In the Gulf of Aqaba, the nitrate deficit was lower with less variance than in the northern Red Sea (Fig. 2, Table 1). This was also reflected in a lower N:P ratio in the northern Red Sea compared to the gulf (Table 1).

The nitrate deficit in the water column was related to the maximum water depth that was considered in the calculations (Fig. 3). Note, that this depth did not correspond at all stations to the water depth (see Table 2). In the northern Red Sea, the water-column nitrate deficit did in addition depend on the location within the basin (compare Fig. 1).

4.3 Nitrate deficit and oxygen

Figure 4a shows an example of typical vertical oxygen profiles in each system. In the Gulf of Aqaba, oxygen concentrations were high even far below the actual mixing depth (200 m, Stn. V, 21 February 1999), where the water neither had contact with the atmosphere nor was enriched with oxygen by phytoplankton production for at least a year. Values below 170 mmol/m^3 we never observed in the gulf (mainly Station I) during the entire study period from 1997 until 1999. By contrast, in the northern Red Sea oxygen concentrations rapidly decreased below the euphotic zone, which exceeded usually the actual mixing depth (50 m, Stn. X, 24/2/1999). A local oxygen minimum of about 80 mmol/m^3 was pronounced at all stations, usually in the 400–600 m depth layer.

The nitrate deficit in both water bodies increased with depth, and inversely reflected the oxygen concentrations (Fig. 4b). In the Gulf of Aqaba, the nitrate deficit of the upper mixed layer was always close to zero, and sometimes even negative (i.e. excess nitrogen) at saturating oxygen concentrations.

The apparent oxygen utilization (AOU) in the water column was linearly related to the water-column nitrate deficit (Fig. 5). The water-column AOU explained 98% of the variance in the water-column nitrate deficit in the Gulf of Aqaba (slope = 0.03, intercept = 0.15 mol m^{-2}), and 82% for the entire data set.

4.4 Preformed nutrients

The relationship of water-column AOU with the amount of phosphate in the water column was highly significant, and followed the same straight line in both water bodies. The slope was very close to the theoretical value of 138 mole O_2 per mole of phosphate according to Redfield et al. (1963). Likewise, was the slope for total oxidized nitrogen quite close to the theoretical value of 8.6 mole O_2 per mole of nitrate in the Gulf of Aqaba. Deviations from that line were observed only in the northern Red Sea, especially at the deeper stations of the basin (Fig. 6). Furthermore, our data indicate that the concentrations of preformed nutrients were small for N and P in both water bodies (not shown).

5 Discussion

In the Gulf of Aqaba, we observed nitrate deficits very close to zero at saturating oxygen concentrations within the mixed layer (see example in Fig. 4). The generally higher nitrate deficit in the northern Red Sea compared to the gulf is either the consequence of lower nitrogen fixation or of higher nitrogen losses in the northern Red Sea. Due to the high oxygen levels in both water bodies, even denitrification in anoxic microzones of aggregates seems to be unlikely (personal communication L. A. Codispoti, S. W. A. Naqvi). Considering the hypsographic characteristics of the steep and nar-

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row basin, benthic denitrification seems to be the main loss process for nitrogen in the Red Sea (personal communication D. M. Sigman). An alternative explanation would be some unrecognized pathway that removes oxidized nitrogen from the ambient water at the presence of high oxygen levels. To further clarify this uncertainty, direct measurements of denitrification rates and other possible loss processes should be undertaken in the area. In addition, vertical fluxes of organic carbon should be considered to make up a budget for benthic denitrification.

5.1 Nitrogen fixation

Trichodesmium blooms are well known to occur in the upper 100 m of the water column in the Gulf of Aqaba, and in the Red Sea (Kimor and Golandski, 1977; Weikert, 1987; Böttger-Schnack and Schnack, 1989; Longhurst, 1998; Post et al., 2002). *Trichodesmium* blooms follow extreme nitrogen depletion, the times of massive occurrence in the area are June, and October/November (Kimor and Golandsky, 1977; Post et al., 2002). The cellular N:P ratio of *Trichodesmium* is often well above the Redfield ratio (Sanudo-Wilhelmy et al., 2001). By subsequent remineralization of a massive *Trichodesmium* bloom, the ambient water becomes enriched with nitrogen relative to phosphorus. The fixed nitrogen is transported into deeper water layers via sedimentation or vertical mixing, and in addition via grazing by the vertically migrating copepod *Macrosetella gracilis*, the main feeder on *Trichodesmium* in the area (Böttger-Schnack and Schnack, 1989). The nitrogen enrichment by *Trichodesmium* was proposed to significantly contribute to the seasonal changes in N:P ratios observed in the gulf (Al-Qutob et al., unpubl. manuscript).

Trichodesmium blooms develop only in stratified waters, as soon as the mixing depth exceeds about 100 m, the bloom ceases (Weikert, 1987; Capone et al., 1997; Post et al., 2002; Tyrrell et al., 2003). Therefore, it seems unlikely that nitrogen fixation by *Trichodesmium* is lower in the stratified northern Red Sea than in the Gulf of Aqaba where deep winter mixing occurs regularly. Furthermore, a possible difference in nitrogen fixation between the two water bodies could hardly be explained by iron limitation

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of nitrogen fixation due to high deposition of dust from the surrounding deserts in the entire area.

In tropical and subtropical oligotrophic oceans *Trichodesmium* is considered the main nitrogen fixing organism (Capone et al., 1997, 2005). In addition, there is recent evidence for a significant contribution to nitrogen fixation by unicellular cyanobacteria (Zehr et al., 2001; Montoya et al., 2004). The contribution of unicellular cyanobacteria to nitrogen fixation in the Red Sea is to the best of our knowledge unclear, so far. A recent study on the distribution of unicellular diazotrophs along a transect from the Seychelles to Oman revealed a considerably reduced abundance of these organisms at water temperatures below 29°C (Mazard et al., 2004). Even in the southern Red Sea, temperatures in this range are restricted to limited time periods (Sofianos et al., 2002), which may severely constrain a significant contribution of these organisms to nitrogen fixation in the northern Red Sea.

5.2 Nitrogen losses

The fact that the nitrate deficit in both water bodies inversely reflected the oxygen concentration throughout the water column (Fig. 4) strongly suggests that the formation of the nitrate deficit is regulated by the level of oxygen.

Considering benthic denitrification as the main loss process for nitrogen in the Red Sea, the observed pattern in the water chemistry can be explained only by a strong benthic-pelagic coupling in the system. Remineralization rates are supposed to be fast in the high-temperature environment of both water bodies. The location of the oxygen minimum indicates the depth layer where the losses of oxidized nitrogen are most pronounced (Fig. 4). This implies that the oxygen level in the water column affects to some extent the denitrification rates in the corresponding sediment layers around the basin. On the other hand, the linear relationship between the AOU and the nitrate deficit in the water column (Fig. 5) implies that benthic denitrification removes nitrate from the water column, even at locations far from the shore (Fig. 1). This requires a strong physical interaction between water and sediment, and can be explained only by intensive horizontal water circulation in the narrow and steep basins of the Red Sea, and the Gulf of Aqaba (Wolf-Vecht et al., 1992; Manasrah et al., 2004). The overall difference in the nitrate deficit between the two water bodies would then be attributable to the different water residence times in the two basins.

The data presented in Figs. 5 and 6 suggest that the nutrient regime especially in the gulf is in accordance with the "Redfield" stoichiometry, and is mainly ruled by internal biogeochemical cycles. Both relationships revealed a higher variance in the northern Red Sea than in the gulf (Figs. 5 and 6). Deviations occurred in particular at the deep stations in the northern Red Sea and at the most western station (Fig. 1), which seems to be related to the longer residence time of deep and bottom water compared to that in the upper layers, and to the exchange of water masses between the northern Red Sea and the two adjacent gulfs (Aqaba and Suez) at the different stations (Plähn et al., 2002).

From the difference in the two systems we conclude that the process responsible for the nitrogen losses in the system is suppressed by high oxygen concentrations in the gulf. In this context, the deep winter mixing plays a key role by resetting the oxygen concentrations back to the saturation value within the mixed layer.

5.3 The role of iron for the nitrogen budget

As nitrogen fixation seems to be released from iron limitation in the region of the Red Sea, one should expect that the nitrate deficit would disappear, and N:P ratios would increase to values close to the Redfield ratio. This was observed only in the Gulf of Aqaba, but not in the northern Red Sea. Consequently, a different mechanism must be responsible for the nitrate deficit observed in the northern Red Sea.

Tyrrell (1999) pointed out that an overall ocean nitrate deficit is compatible with a system in steady state which can be attributed to the competition between nitrogen fixers and other phytoplankton. Nitrogen fixers pay higher energetic costs for fixing nitrogen than non-fixing phytoplankton, which results in lower maximum growth rates (Capone et al., 1997; Tyrrell, 1999).

Moreover, recent studies report that nitrogen fixation rates in the central Atlantic Ocean seem to be rather stimulated by phosphate-containing dust than by levels of dissolved iron in the ambient water (Sañudo-Wilhelmy et al., 2001; Tyrrell et al., 2003).

5.4 Concept of PLN and ULN

In conclusion of all the different mechanisms and processes considered above, we propose that benthic denitrification as the loss process in *combination* with the competition between nitrogen fixers and other phytoplankton causes the nitrate deficit in the waters of the oligotrophic Red Sea. If the loss process is suppressed, as we observed in the Gulf of Aqaba, the result is an N:P ratio very close to "Redfield". This clearly supports the concept that phosphate is the ultimate limiting nutrient for primary production, which should not be neglected in the efforts that are undertaken for protecting the marine systems against eutrophication. In the Gulf of Aqaba, the industrial mining and subsequent shipping of phosphate leads to episodic phosphorus enrichment of surface waters (Klinker et al., 1978), which on the long term might be a threat for the adjacent coral reefs in the area. The negative consequences of high nutrient inputs for the coral reefs in the Gulf of Aqaba was drastically demonstrated by an intense winter mixing after the eruption of mount Pinatubo (Genin et al., 1995).

6 Conclusions

The differences in the hydrodynamic regime between the Gulf of Aqaba and the northern Red Sea were found to have far reaching consequences for the nitrogen budget in the two water bodies. From our study we conclude the following:

1. The process responsible for nitrogen losses was suppressed by high oxygen concentrations in the gulf due to deep winter mixing.

2. If both nitrogen fixation and the loss process took place, as observed in the northern Red Sea, the result was a positive nitrate deficit in the ambient water which could not be attributed to iron limitation of nitrogen fixation.

3. Our field data strongly support the concept of phosphate as the ultimate limiting nutrient for primary production in the sea (Tyrrell, 1999). This concept should be considered for protecting the coral reefs in the Red Sea, and marine environments in general against eutrophication.

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Table 1. Comparison of the "Redfield" characteristics in the Gulf of Aqaba and the northern Red Sea. N:P ratios and nitrate deficits were calculated from pairs of total oxidized nitrogen and phosphate concentrations collected from all stations in both systems. Differences in N:P ratios between the two systems were tested by a General Linear Model ($p<0.005$), nitrate deficits were compared by a two-sided t-Test ($p=9.9\times10^{-10}$).

		N:P ratio			Nitrate deficit (mmol/m^3)	
Statistical measure	n	slope	intercept	r^2	Mean	SD
Gulf of Aqaba	151	13.1±0.3	0.1±0.1	0.94	0.3	0.6
Northern Red Sea	79	11.3±0.4	0.2±0.3	0.90	2.2	2.4

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Table 2. Water column chemistry at the different stations sampled in the Gulf of Aqaba and the northern Red Sea. Note that the maximum sampling depth did not correspond at all stations to the water depth.

Station		Latitude	Longitude	Date	Water depth (m)	Max. spl. depth (m)	N deficit (mol/m^2)	AOU (mol/m^2)
Gulf of Aqaba								
I	122/9	29.492N	34.950E	22/02/1999	600	500	0.22	0.4
II	121/7	29.283N	34.816E	22/02/1999	850	845	0.76	–
II	123/10	29.284N	34.815E	22/02/1999	850	845	–	18.5
III	124/12	29.083N	34.766E	22/02/1999	835	835	0.68	–
III	137/27	29.084N	34.767E	26/02/1999	840	470	0.18	1.8
IV	125/13	28.833N	34.734E	23/02/1999	1445	1400	1.26	–
IV	136/26	28.834N	34.733E	25/02/1999	1415	1400	–	43.3
V	118/4	28.582N	34.651E	21/02/1999	1200	1200	1.00	–
V	126/14	28.584N	34.650E	23/02/1999	1200	300	0.08	0.6
V	126/15	28.584N	34.650E	23/02/1999	1200	1200	–	33.6
VI	117/3	28.337N	34.551E	21/02/1999	885	790	0.52	13.9
Northern Red Sea								
VII	144/35	27.880N	34.666E	27/02/1999	665	665	1.52	52.6
VIII	145/36	27.654N	34.668E	27/02/1999	900	900	1.80	85.6
IX	130/19	27.418N	34.668E	24/02/1999	880	880	3.32	–
X	131/20	27.184N	34.666E	24/02/1999	1140	1140	5.30	101.7
XI	132/22	27.298N	34.367E	24/02/1999	1325	1325	4.93	119.1
XII	149/42	27.417N	34.084E	28/02/1999	815	815	0.54	47.8

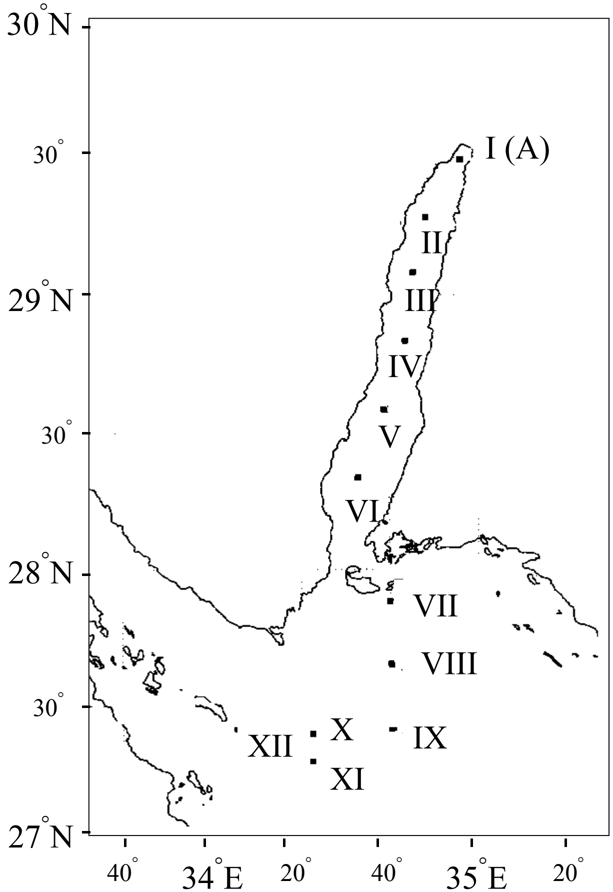

Fig. 1. Map of the study site indicating stations for water sample collection in the Gulf of Aqaba and the northern Red Sea during the RV "Meteor" cruise 44/2.

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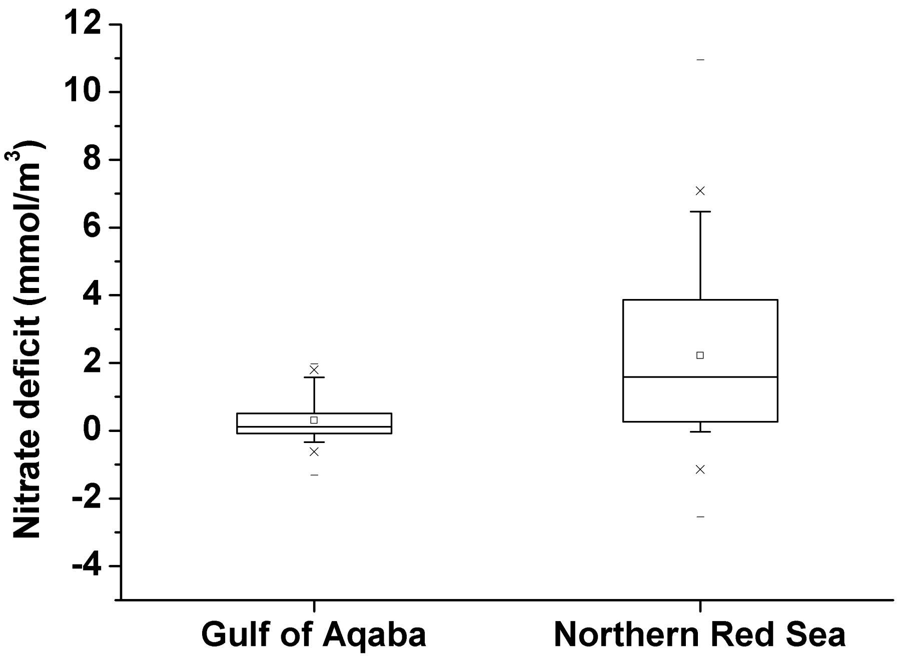

Fig. 2. Box-Whisker Plot of the nitrate deficit in both systems (numbers are given in Table 1).

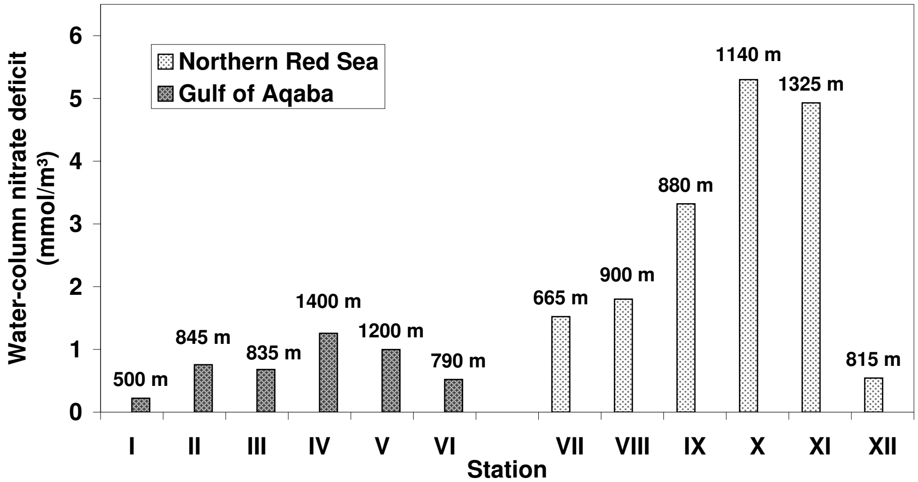

Fig. 3. Horizontal distribution of the water-column nitrate deficit in the Gulf of Aqaba (Stations I–VI), and in the northern Red Sea (Stations VII–XII; see Fig. 1). The values of the water-column nitrate deficits are given in Table 2. The indicated depths refer to the maximum depth that was sampled at the respective station (see Table 2).

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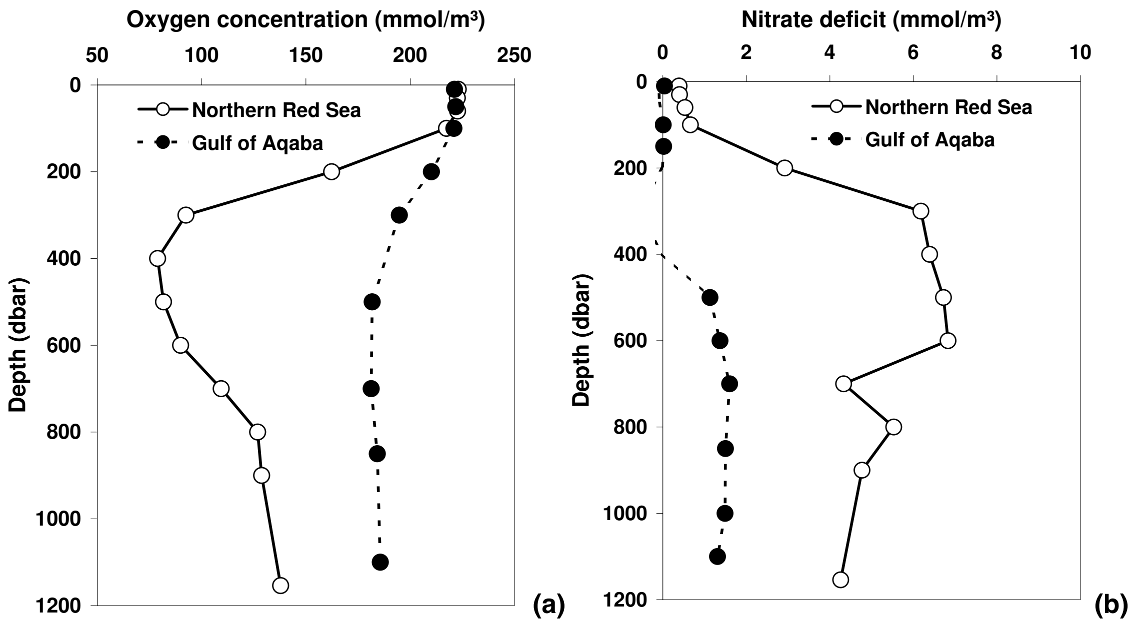

Fig. 4. (a) Typical vertical oxygen distribution in the Gulf of Aqaba and the northern Red Sea. **(b)** Corresponding vertical distribution of the nitrate deficit. Data from 21/2/1999, Station V, and from 24/2/1999, Station X.

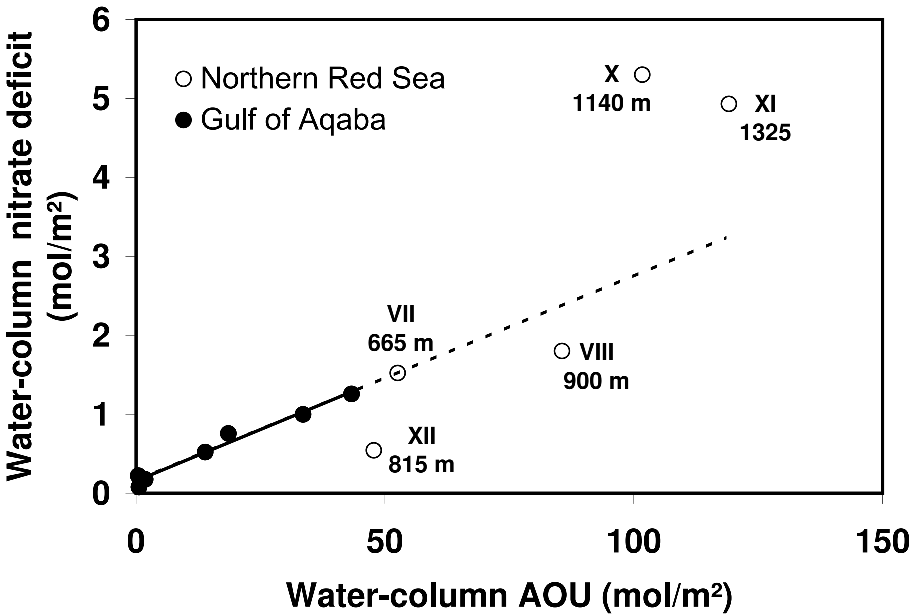

Fig. 5. (a) The nitrate deficit versus oxygen concentration in the Gulf of Aqaba and in the northern Red Sea. Note, that for stations IV and V nutrient and oxygen data are not from the same day (see Table 2). Note also, that the trendline corresponds to the data from the gulf, only. Station numbers and maximum sampling depths are indicated (Table 2).

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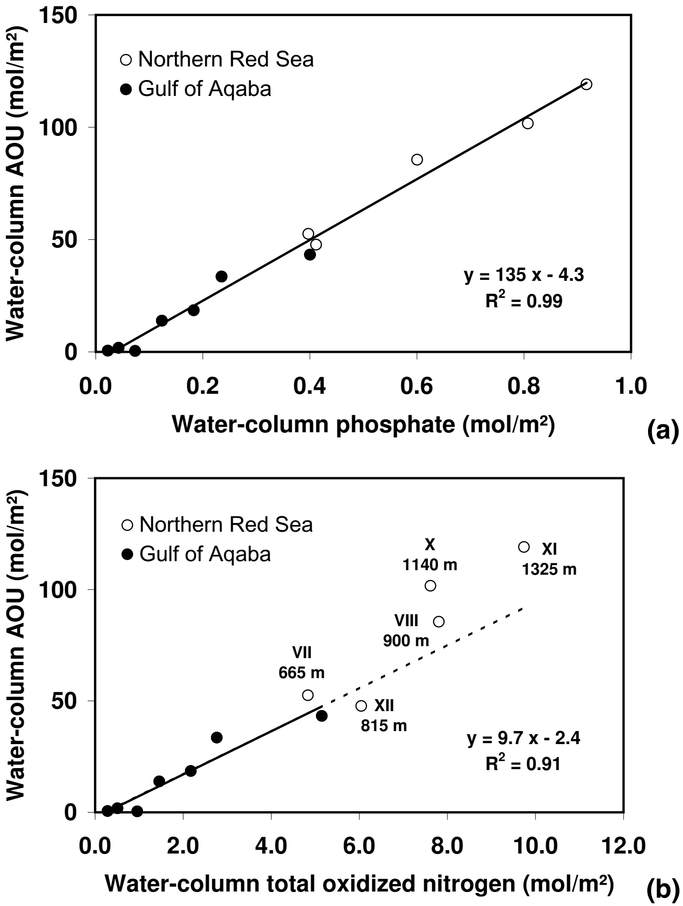

Fig. 6. Apparent oxygen utilization and nutrient remineralization of **(a)** phosphate, and **(b)** total oxidized nitrogen follow the "Redfield" stoichiometry in the Gulf of Aqaba and in parts of the northern Red Sea. Note, that for stations IV and V nutrient and oxygen data are not from the same day (see Table 2). Station numbers and maximum sampling depths are indicated (Table 2).

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